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"Evaluation and Understanding of the Laser Oscillation Property in Waveguides"

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by

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14. ABSTRACT
Excellent beam quality is indispensable for industrial application of high power lasers. However, high-power laser oscillation produces temperature gradients and thermal lensing inside the laser gain media resulting in laser power breakdown. This report describes fabrication of waveguide structures using Nd:YAG and YAG ceramics and investigation of their laser oscillation properties. The ceramic laser gain media evaluated was fabricated using materials controlled at macro-, micro- and nano-levels, and bonded into stacked waveguides which showed that generation of a high-power laser from a small gain medium (10mm x 32 mm) is possible. Laser output power was determined for a series of input power ranges (100-300 W, 400-600 W) and was found to increase rapidly almost linearly at 80 W or more absorbed power. Maximum output, 266 W, was momentarily achieved at approximately 680 W of absorbed power with over 46% slope efficiency without cracking the sample. Saturation of output power occurred at 260 W or greater absorbed power.

15. SUBJECT TERMS
Lasers, Transparent Ceramics, Waveguides, Polycrystalline Materials

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Title of Project: “Evaluation and understanding of the laser oscillation property in waveguides”

Abstract

High power laser having excellent beam quality is indispensable for industrial application such as the processing. However, for high-power laser oscillation, temperature gradient and thermal lensing occur inside laser gain media resulting from high-input power density. Moreover, laser power breakdown occurs when input power is supplied to an extent. In this work, we fabricated waveguide structure with Nd:YAG and YAG ceramics, and investigated their laser oscillation property. Based upon the results of this work, we will develop high-power waveguide laser reducing thermal influence such as temperature gradient and thermal lensing for industrial application in the future.

Keywords: Transparent ceramics, transparent polycrystalline material, waveguide laser, bonding technology

1. Introduction

Ceramic technology can provide microstructure and macrostructure in combination with innovative and novel system configuration of the ceramic gain media. We must focus on these advantages of ceramics to develop novel technologies which cannot be realized in single crystal materials. The ceramic laser gain media to be fabricated is controllable in macro-, micro- and nano-structural level, and generation of high-power laser from a small gain medium is possible, and this novel technology will become very important in laser engineering field.

Thermo-mechanical issues are very serious in high-power laser generation. Temperature gradient occurs in the laser gain medium at cross-sectional direction due to the heating at the central region and due to the cooling at the outer region of the laser gain medium during high power laser operation. Accordingly, the distribution of refractive index becomes inhomogeneous due to the thermal lensing effect, and the beam quality of the generated laser beam is badly degraded. Moreover, laser power breakdown occurs when input power is supplied to an extent. The advantage of a waveguide type laser is the cooling from the large surface that can suppress thermal gradients inside the core. Thus, the above mentioned localized heat generation issues can be neglected, and thermal lens effect and optical anisotropy are remarkably reduced. In contrast, the long propagation length of pumping beam can generate laser output power effectively (high-gain and high-efficiency).

2. Objective of the project

The objective of the project is to fabricate waveguide structure with Nd:YAG and YAG ceramics, and investigate their laser oscillation property. The Material team will fabricate waveguide structures by using Nd:YAG and YAG ceramics. Bonding is the key technology to realize a planar waveguide structure with YAG materials. The Laser team will investigate their laser oscillation properties.

3. Project schedule and targets

The project will proceed by fabrication of waveguide structure, and investigation of laser oscillation properties. Waveguide sample fabrication and its evaluation will be involved: (1) evaluate performance of the laser waveguide to produce 100 - 200 watts(1st stage), (2) evaluate performance of the laser waveguide to produce 200 - 300 watts(2nd stage), and (3) evaluate performance of the laser waveguide to produce 400 - 600 watts(3rd stage).

4. Fabrication of waveguide sample

Thermal conductivity for ceramic is close to that of single crystal YAG. High thermal conductivity materials can contribute to high power laser operation. Furthermore, waveguide type laser can suppress the heat gradient in the core to have a wide cooling surface (Fig. 1). For this reason, localized heat generation issues can be neglected, and thermal lens effect and optical anisotropy are remarkably reduced. TIR with the long propagation length of pumping beam can generate laser output power effectively (high-gain and high-efficiency). For this purpose, sapphire was used as cladding in three levels of core (YAG-Nd:YAG-YAG) opposite sides. The oscillation direction of the sample is decided by the number of a LD for the pumping which target output can achieve.

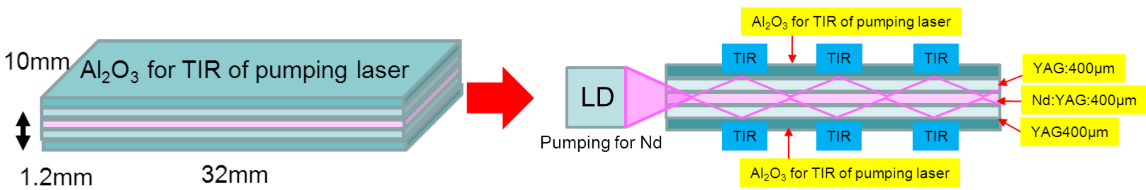
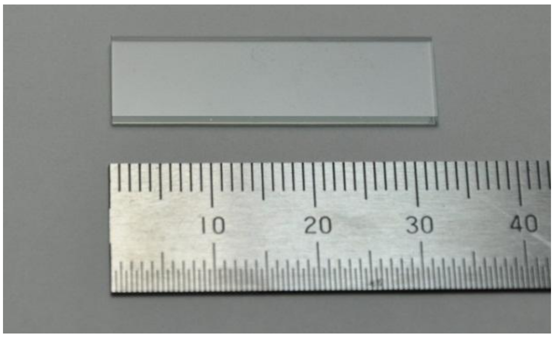
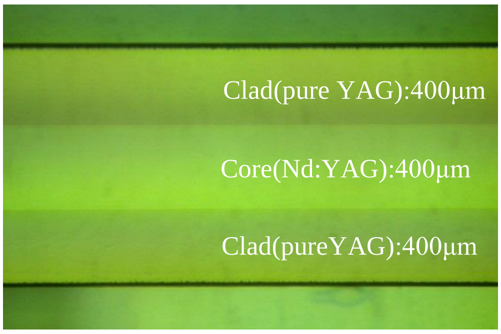


Fig 1. Design of the waveguide sample.

We prepared both YAG ceramic with one surface polished and Nd: YAG ceramics with both surfaces polished. After Nd:YAG ceramics were contacted with previous YAG ceramic, the contacted samples were heated over 1000 degrees Celsius. Waveguide ceramic sample of 32 mm x 10 mm was successfully fabricated by using a bonding technology to achieve output target of the 1st stage (100 W - 200 W) and the 2nd stage (200 W - 300 W). All samples used in this project were manufactured by Dr. Ikesue of World Laboratory Co., Ltd. The photograph of a fabricated sample is shown in figure 2(a). A laser active layer (e.g., Nd:YAG with 400 µm thickness and 0.6 at% doping) is arranged at the center, and low refractive index materials (high thermal conductive material: pure YAG with 400 µm thickness) is strongly bonded at the atomic level on both faces. Each thickness of pure YAG is 400 µm resulting in a thickness of 1.2 mm for the whole sample. From microphotography, the interfacial condition of the bonded area is excellent (Fig. 2(b)). In this experiment, the pumping light was incident from the one side of the 10 mm x 1.2 mm surface or the opposite sides. Gradient processing (3 degree and 4 degree) was made on 1.0 mm x 1.2 mm surface to prevent ASE in the pumping direction. Power density of the pump beam determined the thickness of YAG and the Nd:YAG.





(a) (b)

Fig. 2(a) Photograph of the sample with 400 µm thickness core, (b) Micro photography of the bonding boundary surface.

5. Laser oscillation property for 100 W to 300 W

Several LD stacks of 808nm were used for a laser oscillation experiment as a pumping laser light. Maximum output per one LD is approximately 400 W. The pumping laser light was incident from edge face of 1.2 mm x 10 mm of the sample as shown in Fig. 3(a). As for the pump beam, the vertical direction was focused in the sample inside by a focusing unit, and the horizontal made a collimated beam. A vertical focusing condition was adjustable from 400 µm to 1000 µm. The horizontal beam can propagate up to about 70 mm in parallel light with width of 9 mm. The waveguide sample was attached in a copper heat sink by using heat conduction grease. The heat sink cooled off in two thermo-electronic cooler (TEC: 100

W). AR coating was coated for all the edge face of the sample. The sample was put between two flat mirrors and constituted a resonator (Fig. 3(b)). The mirror of 20 % of transmittance was selected as an output coupler (O. C.). The resonator length was approximately 13 mm. In this condition, input pump power of 10 % or more become the transmitted leak power.

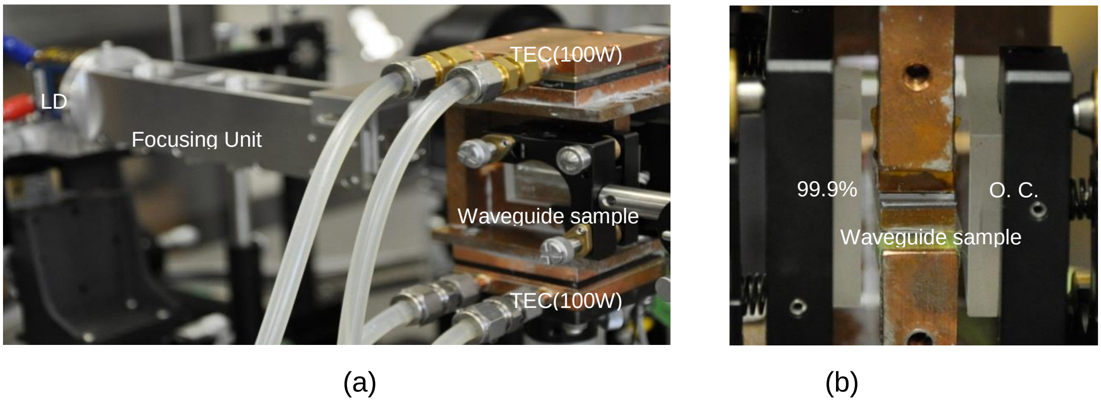


Fig. 3(a) Schematic layout of the laser oscillation experiment, (b) Side-view of the sample holder

A sample was pumped using one LD stack to achieve output target from 100 W to 200 W (1st stage). The relationship between absorbed pump power and output power is shown in figure 4. The laser output was taken out from the surface of 1.2 mm x 32 mm. As absorbed powers increased, the laser output rapidly increased. At the region with 80 W or more absorbed power, output power almost increases linearly. Maximum output, 120 W, was obtained from approximately 260 W of absorbed power. Over 50 % of slope efficiency was achieved without cracking the sample. However, in the region with 260 W or more absorbed power, saturation of the output power occurred.

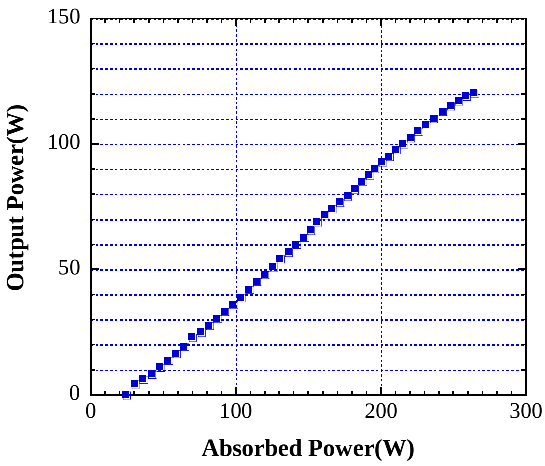


Fig. 4. Relationship between absorbed power and output power for target output from 100 W to 200 W (1st stage).

The saturation of this output is thought to be caused by a thermal factor. For this experiment, coolability is thought to be just short at the maximum output of 120 W. To obtain higher output power, introducing the high-power sample cooling system is indispensable.

To accomplish output power from 200 W to 300 W (2nd stage), we changed TEC from 100 W to 200 W to improve coolability. The coolability became 400 W in two improved TECs. Furthermore, the pumping LD source with a focusing unit increased from one to two to pump a sample from the opposite sides. The relationship between absorbed power and output power for experiment of 2nd stage is shown in figure 5.

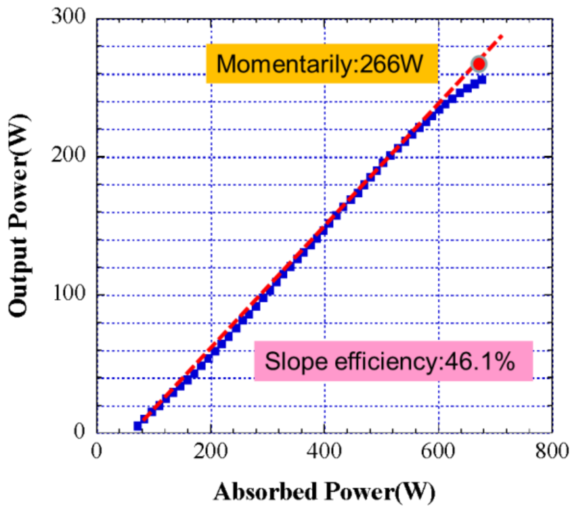


Fig. 5. Relationship between absorbed power and output power for target output from 200 W to 300 W (2nd stage).

Pumping laser output was increased slowly while being careful about the temperatures in the resonator enough. The laser output increased linearly, but laser output has begun to be saturated from the absorbed power of 600 W. Slope efficiency of 46 % was achieved without cracking the bonding interface. In contrast, pumping laser output was increased relatively early and evaluated maximum output. Maximum output 266 W was momentarily obtained at absorbed power of approximately 680 W. As a result, the coolability of the sample was found to be a problem in this experiment. The heat generated in a sample cools it from a top and the undersurface of 10 mm x 32 mm. For the improvement of the cooling efficiency, necessary the gimmicks such as large sample surface area and the improvement of thermal conductance such as the grease.

6. Laser oscillation property for 400 W to 600 W

For further power scaling of the laser output, a new sample holder was designed and fabricated. Available LDs for pumping can be increased to up to four depending on a sample size. Figure 6 shows experimental arrangements for pumping with three LDs and four LDs. For the sample length of the resonance direction around 30mm, three LD stacks (total output: 1,200 W) are used for pumping. Furthermore, when the sample length of the resonance direction is around 60mm, four LDs (total output: 1,600 W) are used for pumping by two from right and left. Focusing units for two LD stacks arranged with 15 mm width are fabricated for this purpose (Fig. 7). Because this focusing unit is attached to highly precise stage, it can perform the fine tuning of the incidence condition to a waveguide sample easily.

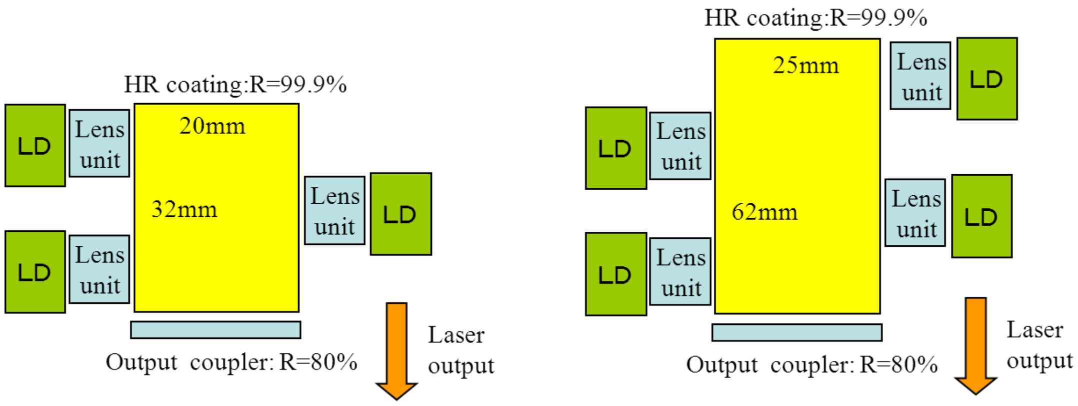


Fig. 6. Experimental arrangements for pumping with three LDs and four LDs

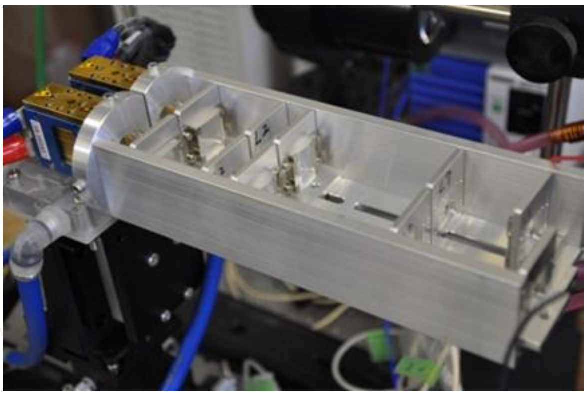
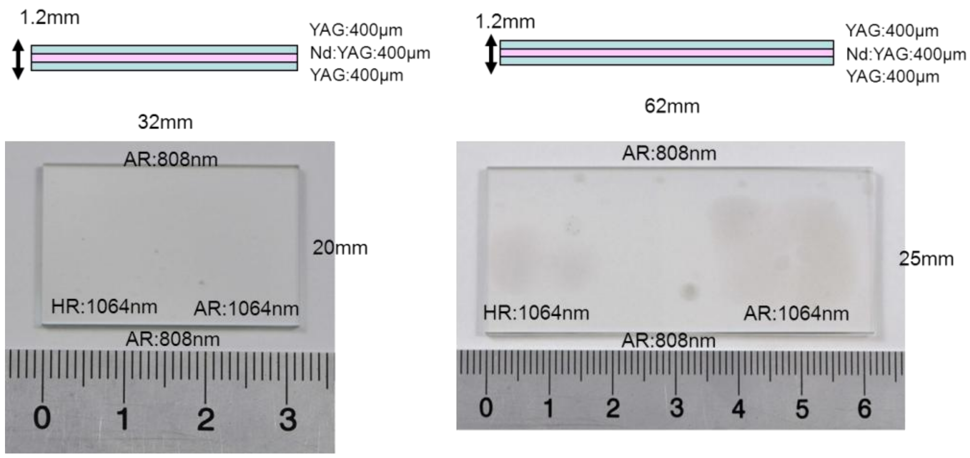


Fig. 7. Focusing unit for two LD stacks arranged with 15 mm width.

Several large waveguide samples were prepared for further power scaling of the laser output. The photographs of a fabricated sample are shown in figure 8 (a), (b). The Nd doping of waveguide sample:32 mm x 20 mm is 0.6at%. In contrast, The Nd doping of waveguide sample:62 mm x 25 mm is 0.3at%. As for all samples, thickness of the Nd:YAG is 400μm. The thickness of YAG bonded together up and down of the Nd:YAG is 400μm, respectively. AR (808 nm or 1064nm), HR (1064 nm) coating are put for each side of the sample. Therefore, it was not necessary to use the total reflection mirror part of 1064nm. New TEC was installed in the space of eliminated mirror holder. As a result, coolability of TEC can be increased to up to 1,000 W. An oscillation experiment was performed in these samples, but did not reach the satisfied power level. New optimized samples are being processed. The oscillation experiment of higher output is going to be reported in other grant "Basic Research for AOARD 114082 "High-power laser oscillation test using ceramic waveguide".



(a) (b)

Fig. 8. (a) waveguide sample: 32 mm x 20 mm with 0.6at% doping, (b) waveguide sample: 62 mm x 25 mm with 0.3at% doping

7. Conclusions

Evaluation of waveguide samples were performed in this project. We have successfully fabricated a waveguide structure with Nd:YAG and YAG ceramics by using a bonding technology. A laser active layer (e.g., Nd:YAG with 400 μm thickness and 0.6 at% doping) is arranged at the center, and low refractive index materials (high thermal conductive material: pure YAG with 400 μm thickness) is strongly bonded at the atomic level on both faces of it. Sapphire was used as cladding in three levels of core (YAG-Nd:YAG-YAG) opposite sides. Maximum output 266 W was successfully obtained from approximately 680 W of absorbed powers in 10mm x 32 mm waveguide sample. Over 46% of slope efficiency was achieved (target of in this grant) without cracking the sample. Furthermore, for obtaining higher output power, new sample holder and focusing unit, increased coolability, and large-sized wavegide sample were prepared. Oscillation experiments were performed in advanced experimental setup, but did not reach the satisfied power level. A material team performs the re-manufacture of a new optimized sample now. The oscillation experiment of higher output is going to be reported in other grant "Basic Research for AOARD 114082 "High-power laser oscillation test using ceramic waveguide".

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List of Publications

"All ceramic Nd:YAG waveguide laser element with perfect bonding condition (Invited Paper)", Photonics West 2012.